1. RADIOACTIVITY and RADIATION PROTECTION

Revised August 2011 by S. Roesler and M. Silari (CERN).

1.1. Definitions [1,2]

1.1.1. *Physical quantities*:

• **Fluence,** Φ (unit: $1/\mathrm{m}^2$): The fluence is the quotient of dN by da, where dN is the number of particles incident upon a small sphere of cross-sectional area da

$$\Phi = dN/da \ . \tag{1.1}$$

In dosimetric calculations, fluence is frequently expressed in terms of the lengths of the particle trajectories. It can be shown that the fluence, Φ, is given by

$$\Phi = dl/dV,$$

where dl is the sum of the particle trajectory lengths in the volume dV.

• **Absorbed dose,** D (unit: gray, 1 Gy=1 J/kg=100 rad): The absorbed dose is the energy imparted by ionizing radiation in a volume element of a specified material divided by the mass of this volume element.

• **Kerma,** K (unit: gray): Kerma is the sum of the initial kinetic energies of all charged particles liberated by indirectly ionizing radiation in a volume element of the specified material divided by the mass of this volume element.

• **Linear energy transfer,** L **or** LET (unit: J/m, often given in keV/μm): The linear energy transfer is the mean energy, dE, lost by a charged particle owing to collisions with electrons in traversing a distance dl in matter. *Low-LET radiation:* x rays and gamma rays (accompanied by charged particles due to interactions with the surrounding medium) or light charged particles such as electrons that produce sparse ionizing events far apart at a molecular scale ($L < 10$ keV/μm). *High-LET radiation:* neutrons and heavy charged particles that produce ionizing events densely spaced at a molecular scale ($L > 10$ keV/μm).

• **Activity,** A (unit: becquerel, 1 Bq=1/s=27 picocurie): Activity is the expectation value of the number of nuclear decays occurring in a given quantity of material per unit time.

1.1.2. *Protection quantities*:

Protection quantities are dose quantities developed for radiological protection that allow quantification of the extent of exposure of the human body to ionizing radiation from both whole and partial body external irradiation and from intakes of radionuclides.

• **Organ absorbed dose,** D_T (unit: gray): The mean absorbed dose in an organ or tissue T of mass m_T is defined as

$$D_T = \frac{1}{m_T}\int_{m_T} D dm \ .$$

• **Equivalent dose,** H_T (unit: sievert, 1 Sv=100 rem): The equivalent dose H_T in an organ or tissue T is equal to the sum of the absorbed doses $D_{T,R}$ in the organ or tissue caused by different radiation types R weighted with so-called radiation weighting factors w_R:

$$H_T = \sum_R w_R \times D_{T,R} \ . \tag{1.2}$$

It expresses long-term risks (primarily cancer and leukemia) from low-level chronic exposure. The values for w_R recommended by ICRP [2] are given in Table 1.1.

Table 1.1: Radiation weighting factors, w_R.

Radiation type	w_R
Photons, electrons and muons	1
Neutrons, $E_n < 1$ MeV	$2.5 + 18.2 \times \exp[-(\ln E_n)^2/6]$
$1 \text{ MeV} \leq E_n \leq 50$ MeV	$5.0 + 17.0 \times \exp[-(\ln(2E_n))^2/6]$
$E_n > 50$ MeV	$2.5 + 3.25 \times \exp[-(\ln(0.04E_n))^2/6]$
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20

• **Effective dose,** E (unit: sievert): The sum of the equivalent doses, weighted by the tissue weighting factors w_T ($\sum_T w_T = 1$) of several organs and tissues T of the body that are considered to be most sensitive [2], is called "effective dose":

$$E = \sum_T w_T \times H_T \ . \tag{1.3}$$

1.1.3. ***Operational quantities***:

The body-related protection quantities, equivalent dose and effective dose, are not measurable in practice. Therefore, operational quantities are used for the assessment of effective dose or mean equivalent doses in tissues or organs. These quantities aim to provide a conservative estimate for the value of the protection quantity.

• **Ambient dose equivalent,** $H^*(10)$ (unit: sievert): The dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in a 30 cm diameter sphere of unit density tissue (ICRU sphere) at a depth of 10 mm on the radius vector opposing the direction of the aligned field. Ambient dose equivalent is the operational quantity for *area monitoring*.

• **Personal dose equivalent,** $H_p(d)$ (unit: sievert): The dose equivalent in ICRU tissue at an appropriate depth, d, below a specified point on the human body. The specified point is normally taken to be where the individual dosimeter is worn. For the assessment of effective dose, $H_p(10)$ with a depth $d = 10$ mm is chosen, and for the assessment of the dose to the skin and to the hands and feet the personal dose equivalent, $H_p(0.07)$, with a depth $d = 0.07$ mm, is used. Personal dose equivalent is the operational quantity for *individual monitoring*.

1.1.4. ***Dose conversion coefficients***:

Dose conversion coefficients allow direct calculation of protection or operational quantities from particle fluence and are functions of particle type, energy and irradiation configuration. The most common coefficients are those for effective dose and ambient dose equivalent. The former are based on simulations in which the dose to organs of anthropomorphic phantoms is calculated for approximate actual conditions of exposure, such as irradiation of the front of the body (antero-posterior irradiation) or isotropic irradiation.

Conversion coefficients from fluence to effective dose are given for anterior-posterior irradiation and various particles in Fig. 1.1 [3]. For example, the effective dose from an anterior-posterior irradiation in a field of 1-MeV neutrons with a fluence of 1 neutron per cm^2 is about 290 pSv. In Monte Carlo simulations such coefficients allow multiplication with fluence at scoring time such that effective dose to a human body at the considered location is directly obtained.

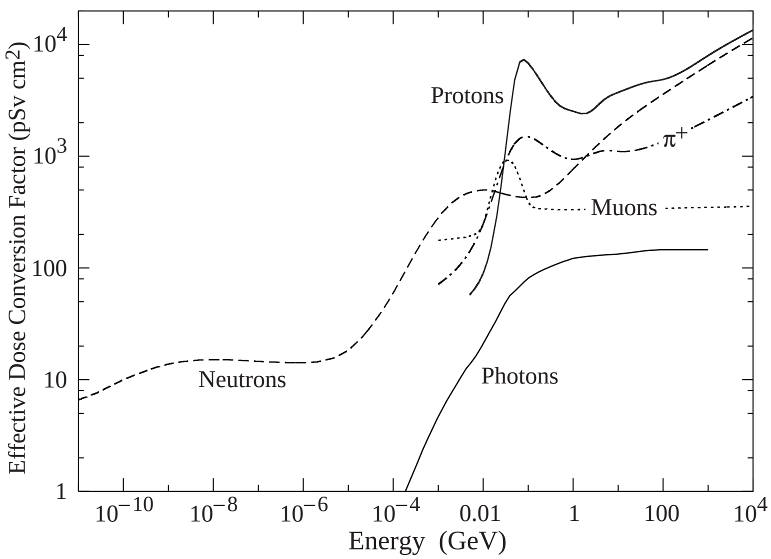

Figure 1.1: Fluence to effective dose conversion coefficients for anterior-posterior irradiation and various particles [3].

1.2. Radiation levels [4]

• **Natural background radiation**: On a worldwide average, the annual whole-body dose equivalent due to all sources of natural background radiation ranges from 1.0 to 13 mSv (0.1–1.3 rem) with an annual average of 2.4 mSv [5]. In certain areas values up to 50 mSv (5 rem) have been measured. A large fraction (typically more than 50%) originate from inhaled natural radioactivity, mostly radon and radon daughters. The latter can vary by more than one order of magnitude: it is 0.1–0.2 mSv in open areas, 2 mSv on average in a house and more than 20 mSv in poorly ventilated mines.

• **Cosmic ray background radiation**: At sea level, the whole-body dose equivalent due to cosmic ray background radiation is dominated by muons; at higher altitudes also nucleons contribute. Dose equivalent rates range from less than 0.1 μSv/h at sea level to a few μSv/h at aircraft altitudes. Details on cosmic ray fluence levels are given in the Cosmic Rays section (Sec. 26 of this *Review*).

• **Fluence to deposit one Gy**: *Charged particles:* The fluence necessary to deposit a dose of one Gy (in units of cm^{-2}) is about $6.24 \times 10^9/(dE/dx)$, where dE/dx (in units of MeV g^{-1} cm^2) is the mean energy loss rate that may be obtained from Figs. 30.2 and 30.4 in Sec. 30 of this *Review*, and from `http://pdg.lbl.gov/AtomicNuclearProperties`. For example, it is approximately 3.5×10^9 cm^{-2} for minimum-ionizing singly-charged particles in carbon. *Photons:* This fluence is about $6.24 \times 10^9/(Ef/\ell)$ for photons of energy E (in MeV), an attenuation length ℓ (in g cm^{-2}), and a fraction $f \lesssim 1$, expressing the fraction of the photon energy deposited in a small volume of thickness $\ll \ell$ but large enough to contain the secondary electrons. For example, it is approximately 2×10^{11} cm^{-2} for 1 MeV photons on carbon ($f \approx 1/2$).

1.3. Health effects of ionizing radiation

Radiation can cause two types of health effects, deterministic and stochastic:

• **Deterministic effects** are tissue reactions which cause injury to a population of cells if a given threshold of absorbed dose is exceeded. The severity of the reaction increases with dose. The quantity in use for tissue reactions is the absorbed dose, D. When particles other than photons and electrons (low-LET radiation) are involved, a Relative Biological Effectiveness (RBE)-weighted dose may be used. The RBE of a given radiation is the reciprocal of the ratio of the absorbed dose of that radiation to the absorbed dose of a reference radiation (usually x rays) required to produce the same degree of biological effect. It is a complex quantity that depends on many factors such as cell type, dose rate, fractionation, etc.

• **Stochastic effects** are malignant diseases and heritable effects for which the probability of an effect occurring, but not its severity, is a function of dose without threshold.

• **Lethal dose**: The whole-body dose from penetrating ionizing radiation resulting in 50% mortality in 30 days (assuming no medical treatment) is 2.5–4.5 Gy (250–450 rad)†, as measured internally on the body longitudinal center line. The surface dose varies due to variable body attenuation and may be a strong function of energy.

• **Cancer induction**: The cancer induction probability is about 5% per Sv on average for the entire population [2].

• **Recommended effective dose limits**: The International Commission on Radiological Protection (ICRP) recommends a limit for radiation workers of 20 mSv effective dose per year averaged over 5 years, with the provision that the dose should not exceed 50 mSv in any single year [2]. The limit in the EU-countries and Switzerland is 20 mSv per year, in the U.S. it is 50 mSv per year (5 rem per year). Many physics laboratories in the U.S. and elsewhere set lower limits. The effective dose limit for general public is typically 1 mSv per year.

See full *Review* for references and further details.

† RBE-weighted when necessary